HINKLEY POINT C PERMIT VARIATION

EPR/HP3228XT/V004

Technical Brief: TB012

Predicting adult sea trout populations in the Severn Estuary.

National Fisheries Service, Environment Agency.

Marine Contractor, APEM LTD.

2020 (DRAFT-03)

INTRODUCTION

The applicant has made estimates of losses to the sea trout (*Salmo trutta*) population of the Severn Estuary from impingement at Hinkley Point C (HPC) based on a run size derived from rod catches in the Severn, Wye and Usk rivers adjusted by exploitation rate. This is a reasonable approach if all the catch data are available and if the exploitation rates are known and appropriate for the rivers in question. Catch data were not available for several other rivers on the English coast of the Severn estuary, and the exploitation rates used are for a range of other rivers around the UK. In the absence of catch data an alternative approach is to estimate sea trout abundance (as annual spawners) from a simple model of abundance *vs* river size. This is the approach taken in this report with the aims of (1) comparing with the applicants estimates and (2) providing estimates of adult runs and spawners for the additional rivers.

The potentially affected rivers

The applicant considered the rivers Severn, Wye, Usk and Taff/Ely (two catchments, with common entrance via the Cardiff Bay Barrage). A further river the Rhymney, which lies east of the Taff/Ely catchment is recommended to be included because it is regarded as a recovering sea trout river by NRW. The rivers draining to the Severn estuary upstream from England are not commonly regarded as productive sea trout rivers. However, the Environment Agency identified sub-catchments in their South West Region that were considered to produce sea trout (Fig 1) and these were used as the areas to be included in the assessment. Therefore this report considers the rivers shown in Table 1. There are also a few rivers in the West Area of the Environment Agency further up the Severn Estuary towards Gloucester (e.g. river Frome, Blakeney Brook, river Chelt) which contain small populations of sea trout but these have not been included and can be considered as part of the river Severn. There is limited data available on these descript areas and the proportion of individuals they contribute to the river Severn are considered minimal.

Methods and data

The assessment was based on a model of spawners predicted from ADF.t (the long term average daily flow at the normal total limit (NTL), calibrated on typical sea trout rivers in Wales. The application of the model to the rivers requiring sea trout estimates in this study has various provisos and adjustments as described below.

Calibration data

For the Taff/Ely, Rhymney, Usk and Wye (the rivers on the Northern shore of the Severn estuary) estimates of annual spawner abundance (mean for years 2006-2016) and river size, indexed by Average Daily Flow (ADF), were made available by NRW, together with a further 28 Welsh rivers that have been used in a recent project on sea trout around Wales. These (but excluding the Wye, which is exceptionally atypical, see below) were used to derive a simple linear regression model from which to predict sea trout spawners from the other rivers (termed the NEW rivers) for which no spawner estimates were available.

Table 1 List of rivers used in model calibration and for estimating sea trout runs.

Type	River	Accessible wetted area (Ha)	Comment
NEW	Severn	898.07	sea trout only in part of catchment
NEW	Wye	1721.04	sea trout only in part of catchment
calibration	Usk	407.09	sea trout only in part of catchment
calibration	Rhymney	NA	discrete, whole catchment
calibration	Taff.Ely	145.72	discrete, whole catchment
calibration	Ogmore	61.21	discrete, whole catchment
calibration	Afan	29.60	discrete, whole catchment
calibration	Neath	55.61	discrete, whole catchment
calibration	Tawe	87.85	discrete, whole catchment
calibration	Loughor	59.78	discrete, whole catchment
calibration	Gwendraeth	NA	discrete, whole catchment
calibration	Tywi	500.07	discrete, whole catchment
calibration	Taf	90.12	discrete, whole catchment
calibration	E.Wcleddau	86.61	discrete, whole catchment
calibration	Nevern	18.55	discrete, whole catchment
calibration	Teifi	325.92	discrete, whole catchment
calibration	Aeron	20.17	discrete, whole catchment
calibration	Ystwyth	46.12	discrete, whole catchment
calibration	Rheidol	30.63	discrete, whole catchment
calibration	Dyfi	179.13	discrete, whole catchment
calibration	Dysinni	31.49	discrete, whole catchment
calibration	Mawddach	56.66	discrete, whole catchment
calibration	Artro	NA	discrete, whole catchment
calibration	Dwyryd	9.24	discrete, whole catchment
calibration	Glaslyn	25.01	discrete, whole catchment
calibration	Dwyfawr	33.31	discrete, whole catchment
calibration	Llyfni	NA	discrete, whole catchment
calibration	Gwyrfai	NA	discrete, whole catchment
calibration	Seiont	21.05	discrete, whole catchment
calibration	Ogwen	23.90	discrete, whole catchment
calibration	Conwy	63.01	discrete, whole catchment
calibration	Clwyd	83.92	discrete, whole catchment
calibration	Dee	617.04	discrete, whole catchment
NEW	Lit.Avon	19.58	discrete, whole catchment
NEW	Bri.Avon	74.51	part catchment (Bristol Avon)
NEW	Chew	10.50	part catchment (Bristol Avon)
NEW	Brue	13.89	discrete, part catchment (Brue)
NEW	Parrett	25.03	part catchment (Parrett)
NEW	Tone	131.20	part catchment (Parrett)
NEW	Doniford	1.92	part catchment (Doniford)
NEW	Monksilver	3.79	part catchment (Doniford)
NEW	Wasford	1.21	discrete, whole catchment
NEW	Avill	4.74	discrete, whole catchment

ADF was used as predictor variable because it has been shown to be a useful predictor of sea trout productivity (indexed by adult run size, or spawners if no fishery) and was considered to be a river size metric readily available to this study. The model and calibration data were based on Welsh rivers that could be reasonably regarded as producing sea trout over most of their accessible wetted area, down to their junction with the Normal Tidal Limit (NTL) and this structure, i.e. the whole catchment down to NTL, was therefore an important criterion for rivers to which the model might be applied to estimate sea trout spawners. However some of the NEW rivers were only part catchments, located some distance upstream from the NTL.

The model makes the assumptions:

(1) the ADF is proportional to wetted area (the habitat variable thought most directly to affect sea trout stock abundance through influence on carrying capacity and sea trout productivity, as indexed by adult run size); and

(2) the sea trout productivity is directly proportional to area (or ADF) at the tidal limit and that the relationship is the same for the calibration rivers as for the new rivers for which predictions are to be made. This requires that the NEW rivers present the same ecological template for sea trout as the calibration rivers.

Accessible Wetted Area and ADF

The first assumption was tested by correlating accessible wetted area in Ha for the Welsh rivers for which it was known with ADF (m3s-1). The relationship was significant ($r = 0.8572$, $n = 28$, $p < 0.005$) (Appendix I), although errors about the values for Wye and Severn were high for arithmetic data. Log-transformed data gave a model with better diagnostics (residual patterns), see Appendix II. Therefore log(ADF) was taken as a satisfactory and acceptable surrogate for wetted area, with appropriate caution over the two largest rivers.

Wetted area and sea trout productivity

The second assumption is problematic in the context of this Severn Estuary study because, on the basis of rod catches, the large rivers that drain to the upper estuary, particularly the Severn, Wye and to lesser extent the Usk, and also the English rivers listed under NEW, have fewer sea trout than would be expected on the basis of their catchment size alone.

The reason for this is thought to involve the factors that determine the influence of anadromy in trout, such as the early freshwater growth patterns as influenced by freshwater productivity, migration risks of long distance migration through large lowland rivers (particularly a problem if the presumed sea trout production areas lie a long distance upstream from the sea) and survival and growth in the coastal zone. Trout (Salmo trutta) are facultatively anadromous (unlike Atlantic salmon) and the likelihood is that many of the sub-catchments of the Severn and Wye and some of the NEW rivers are not conducive to sea trout production. This makes prediction of sea trout abundance on the basis of total catchment size alone subject to considerable error. Moreover the NEW rivers

Furthermore, model predictions based on more typical sea trout rivers may not be valid for the exceptionally large rivers, in which it is thought that sea trout are only produced in certain sub-catchments, or for rivers, such as the English NEW rivers that have hydrologies, or freshwater productivities, that appeared to be significantly different from the calibration rivers. For example, the base flow indices (bfi) of the NEW rivers (mean = 0.584, n = 7) were significantly higher than those for the Welsh group (mean = 0.473, n = 33) (t = 4.491, p = 0.0015). This means that the calibration river hydrologies are more driven by surface water flow than the NEW group.

To reduce the part catchment problem for the NEW rivers, the analysis estimated the sea trout spawners (N) from the model using the ADF.t at NTL. To compensate for the partial use of the catchment by anadromous trout, these estimates (N) were then multiplied by the ratio of accessible wetted area of the named sea trout sub-catchments (AWA.st) to the total accessible wetted area of the whole catchment that drained to the NTL (AWA.t) to give an estimate (Nr) for each river. Therefore Nr = N x (AWA.st/AWA.t).

Sea trout spawner – accessible wetted area model

A generalised linear model of annual sea trout spawners (averages over the period 2006-2016) as response variable and ADF as the predictor variable was derived from 31 Welsh rivers, not including the Severn or Wye . TR456 Ed2 used a 5-year mean (2012-2016) catch to estimate SSB and this same time period was used in the model to make it compatible with the previous estimates. Response and predictor variables were logged to stabilise variances. The models, predictions and 95% prediction limits were calculated using R Version 3.3.0 (R Core Team, 2016). The model outputs were considered for biological realism against rivers that are known sea trout rivers and adjustments made to derive best estimates for sea trout spawner abundance in the Severn Estuary.

RESULTS

ADF-spawner modelling

The mean and median annual spawner abundances of the 31 model calibration rivers were 5,434 and 3,059 respectively (years 2006-2016). These rivers are regarded as productive migratory salmonid rivers dominated by sea trout (except the Usk which has a moderate sea trout run, but a higher salmon run), unlike the rivers of the Severn Estuary (see above) and the median abundance (3,059) sets a reasonable reference point for typical sea trout rivers, exceedance of which by the low sea trout production rivers of the upper Severn estuary, particularly those on the English shore, would be considered to be unlikely.

The model parameter estimates (Appendix II) and diagnostics were satisfactory and the relationship (Fig 2A) was significant ($p < 0.001$), but the precision was very low (Appendix II), with adjusted R^2 of 0.3522 (i.e. 35% of ln.spawner variance was explained by ln.ADF) and wide (asymmetric due to the log-transformation) confidence limits when transformed back to arithmetic values (Appendix III). Correspondingly, model prediction performance (fit vs observed) was weak (Fig 2B) but there were too few data to cross-validate.

Aim (1) Comparison with applicants estimates

The model predictions were summed and compared with the TR456 Ed2 estimates for the rivers they considered (Table 2). The Wye model fit of 21,077 is greatly above the value of 1,455 derived by NRW. The latter value was preferred as more realistic and its ratio with the fitted value (0.069) was used to adjust the Severn fitted value from 29,409 to 2,031 as a best estimate (Table 2). For the other rivers (Usk, Taff.Ely and Rhymney) the model outputs were rejected on the grounds that they great exceeded the spawner estimates and the latter values used as the best estimates. Confidence limits of amended estimates were adjusted proportionally in relation to the model outputs (Table 2).

Table 2 Comparison of annual run (spawners + catch) estimates reported by the applicant (method based on exploitation rates) with ADF-spawner model estimates of spawners and run, and the values derived from NRW spawner estimates based on rod catch, adjusted as described in text. Totals with and without Rhymney are given because that river was not included in the applicants estimate.

River No	ADF	River	original NRW estimate	Model estimates of spawners			"Best" estimates of spawners (and Run in last 2 rows)			Cefas method Run estimates		factor to adjust Best Est. CLs		
				fit	lwr CL	upr CL	central tendency	lwr CL	upr CL	Run.min	Run.max		lwr/fit	upr/fit
1	106.70	Severn	NA	29,409	2,729	316,920	2,031	244	16,944	147	1,079			
2	74.24	Wye	1,455	21,077	2,108	210,715	1,455	175	12,143	255	1,864			
3	26.77	Usk	3,148	8,260	967	70,553	3,148	378	26,267	641	4,696		0.117	8.542
4	6.20	Rhymney	336	2,154	268	17,292	336	40	2,803	NA	NA		0.125	8.026
5	24.61	Taff.Ely	1,527	7,644	903	64,705	1,527	183	12,738	338	2,475		0.118	8.465
	Total Run (spawners+rod catch), ex Rhymney						8,417	1,236	68,349	1,381	10,114	mean =	0.120	8.344
	Total Run (spawners+rod catch), incl. Rhymney						**8,753**	**1,276**	**71,153**					

NB mean value for all welsh rivers used in calibration was 5434
NB median value for all welsh rivers used in calibration was 3059
ratio of Wye observed to modelled estimates 0.0690
mean rod catch 2006-2016 257

We were unable to reproduce exactly the values in the applicant's note for run size (1,141 and 8,357) using their stated method. We adjusted the rod catch for reporting using the EA factor of 1.10 (this has changed recently, but not sufficiently to warrant its use in this data set), where the applicant used declared catch. Using the exploitation rate method on adjusted catches gave values of 1,381 and 10,114 respectively, for the 2006-2016 period. For comparative purposes we calculated Run estimates (on adjusted catch) for common rivers (Severn Wye, Usk, Taff.Ely) using the ADF model to give initial values but, because they were clearly too high, revised those in most cases to the values given by the NRW as used in the calibration set. The spawner estimates were summed with the combined 2000-2016 rod catch of 257 to give total pre-rod fishery run for all rivers combined (Table 2). The best estimate of 8,417 (CLs 1,236 – 68,349), excluding the Rhymney, is directly comparable with the applicant's run midpoint value of 5,748 (range 1,381 - 10,114). The best estimates of run in all rivers (including the Rhymney) combined using the APEM/NRW method was 8,753 (95% CLs 1,276 – 71,153) (Table 2).

Aim (2) Overall seatrout spawner estimates

In order to estimate total spawners for all the river stocks potentially impacted by Hinkley Point, in addition to those described above, the model was applied to the English NEW rivers using the ADF.t. for the main catchment in which each part catchment river lay (Table 3). The model estimates of spawners and confidence limits were adjusted by the proportion (AWA.st/AWA.t) to give Nr, the estimate for spawners for each component river. The summed spawner total for the southern shore rivers was 2,232 (95% CLs 264 – 18,960. There was no way to estimate runs, because catches are not recorded for these rivers; but they will have been very small and spawners can be taken as an approximation of run size.

Table 3 River details, Wetted areas, ADF and spawner estimates for English rivers draining to Severn estuary southern shoreline. AWA.t = total catchment wetted stream area; AWA.st = accessible wetted area considered to produce sea trout; ADF.t = Average daily flow of total catchment at NTL; ADF.st = ADF of sea trout area.

Main catchment	river.name	River and reach extent	GS	Discrete river	AWA.t (Ha)	AWA.st (Ha)	ADF.t (m^3s^{-1})	ADF.st (m3s-1)	BFI	AWA.st/AWA.t	Nr spawners estimate	lower 95%CL	Upper 95% CL
Little Avon	Lit.Avon	Little Avon – NTL - Old Mill, Stone ST6886495576	54008 Berkeley Kennels	Yes	58	19.58	1.20	1.198	0.55	0.338	161	17	1,534
Bristol Avon	Bri.Avon	Bristol Avon – NTL to Swineford Weir ST6915468927	53022 Bath?	No	771	74.51	0.00	20.33	0.56	0.097	725	86	6,127
	Chew	River Chew - B. Avon confluence to Woodborough Mill ST6364764306	53004 Compton Dando	No	771	10.50	0.00	1.187	0.62	0.014	102	12	863
Brue	Brue	River Brue – NTL to Hackness Sluice ST3323246214	52010 Lovington	Yes	184	13.89	4.50	1.93	0.48	0.075	56	6	493
Parrett	Parrett	River Parrett – NTL to Thorney Mill ST4288622621	?	No	489	25.03	9.00	1.21	NA	0.051	155	19	1,242
	Tone	River Tone – Parrett confluence – Bradford on Tone sluice ST1745923192	52005 Bishops Hull	No	489	131.20	9.00	2.997	0.6	0.268	814	102	6,511
Doniford	Doniford	Doniford – Confluence with Monksilver to Sampford Brett weir ST0911139885	51001 Swill Bridge	No	23	1.92	1.00	1.032	0.66	0.083	34	3	332
	Monksilver	Monksilver - ST0727240428		No	23	3.79	1.00	NA	NA	0.165	66	7	655
Washford	Wasford	Washford – NTL - Kentsford Farm weir ST0580742555	51003 Beggearn Huish	No	14	1.21	0.00	0.868	0.62	0.087	36	4	352
Avill	Avill	Avill – NTL to Loxhole Bridge culvert SS9957043966		Yes	18	4.74	0.00	NA	NA	0.263	82	8	851
										SUM=	**2,232**	**264**	**18,960**

Combined with the North shore rivers (including the main Severn) gave a total estimate of 10,985 adult sea trout (approximate 95% CLs, 1,540 to 90,113), of which 80% were derived from the Severn and Welsh rivers (Table 4).

Table 4 Summary of sea trout run estimates for Severn Estuary rivers potentially impacted by Hinkley NNB Power Station.

Location	Run	lower 95%CL	Upper 95% CL	%
North shore rivers (Table 2)	8,753	1,276	71,153	80
South shore rivers (Table 3)	2,232	264	18,960	20
Total	10,985	1,540	90,113	

COMMENT AND CONCLUSIONS

Aim (1) The range of applicant's run estimates was based on the exploitation rates reported by Shields *et al*. (2006). The lower end of that range (given as 2.7% in Shields *op.cit.,* not 2.8% as quoted) was from the River Dee, which is probably closest, in terms of its sea trout production and nature of angling intensity, to the Severn, Wye and Usk. Low sea trout exploitation rates would be expected in these rivers. This suggests that for the rivers (Severn, Wye, Usk, Taff/Ely) the true sea trout abundance lies towards or above the upper end of the applicant's range (10,114) and that the midpoint (5,748 fish) was probably on the low side. The estimate of 8,753, based on the NRW spawner calculations, is considered to be a more reasonable mid-point estimate. Even though in-river natural mortality was excluded in both methods, the central estimate (11,000 fish) is thought unlikely to be an under-estimate of runs back to the river (but see next Aim), but the applicant's midpoint value (5,700) may be low due to the use of the higher exploitation rates. It is suggested that if there were substantial sea trout runs in the English this would undoubtedly figure in rod catches and are very unlikely to have remained unknown to the Environment Agency.

Aim (2) The best estimate of the combined sea trout run in the Severn estuary rivers was 11,000 fish. (95% CLs 1,500 - 90,100). These fish comprise a mixture of whitling and older spawners in the annual run back into the rivers; but there is an additional component of sea trout, being those that are maiden fish which remain at sea for one or more winters. This group is impossible to estimate without detailed knowledge of the age composition, life histories and dynamics of the populations. Based on the studies of the Welsh Dee Stock Assessment Programme, this group could be 45-55% of the n.0+ (whitling) age group (CSTP, 2016). Whitling comprise 67-72% of the adult spawners in the Taff.Ely to Wye rivers (APEM unpublished), so this constitutes a substantial number of fish that are unaccounted for in the in-river entrants. Precision on this is very low, because of limited data on age structure and life histories, but it suggests that 11,000 is actually a minimum estimate of adult fish that might be potentially exposed to Hinkley Point.

The use of the ADF-egg model based on Welsh rivers to estimate eggs for the English rivers can be criticised because the rivers in the two regions are different in morphology and probably their productivity. The English rivers are mostly lowland in nature, have a somewhat different hydrology (see the bfi comparisons) and in some cases are modified in their lower reaches. Arguably in most cases, their ecology is less conducive to sea trout production if the biotic conditions are not limiting juvenile relative growth, which is considered to be an important condition for anadromy in brown trout (Jonsson and Jonsson, 2006, 2018; Dodson et al 2012; Nevoux et al 2017).

The confidence limits of the models were very wide, demonstrating that factors in addition to river size were affecting the incidence of anadromy and thus sea trout runs. Furthermore, errors will have been introduced by the derivation of the primary calibration data, for example due to rod catch recording on which all the inputs, even the NRW spawner abundances, were based. For reasons outlined above it is inconceivable that the upper limit (90,100) would be approached and the NRW spawner estimate of 6,500 (for the Severn and Welsh rivers) sets a likely lower limit. The limits encompass the applicant's values and the central estimate of 11,000 is thought likely to be to a reasonable evaluation of run-to-river size, setting a more likely upper limit; but noting the potential for this to be a substantial underestimate due to the sea trout component over-wintering at sea.

Table 5. Conclusion results

	Used in Applicant's assessment	**Used in Environment Agency's assessment**	
		Predicted	Uncertainty Range
Adult sea trout population estimate	N/A	8,750	6,500 – 11,000

REFERENCES

BEEMS (2019) Revised Predictions of Impingement Effects at Hinkley Point C - 2018. Technical Report TR456 Edition 2, Revision 10. Cefas, Lowestoft.

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Jonsson, B. and Jonsson, N. (2006) Life history of the anadromous trout *Salmo trutta*. *In* G.S. Harris and N.J. Milner. *Sea Trout: Biology, Conservation and Management*. Proceedings of First International Sea Trout Symposium, Cardiff, July 2004. Blackwell Scientific Publications, Oxford, 196 -223

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Nevoux, M., Finstad, B., Davidsen, G., Finlay, R. et al (2019). Environmental influences of life history strategies in partial anadromous brown trout (*Salmo trutta*, Salmonidae)*.* Fish and Fisheries. 2019; 00: 1–32. DOI: 10.1111/faf.12396.

Shields B.A., Aprahamian M.W., Bayliss B.D., Davison I.C., Elsmere P. and Evans R. (2006) Sea Trout (Salmo trutta L.) Exploitation in Five Rivers in England and Wales. Environment Agency. 2006.

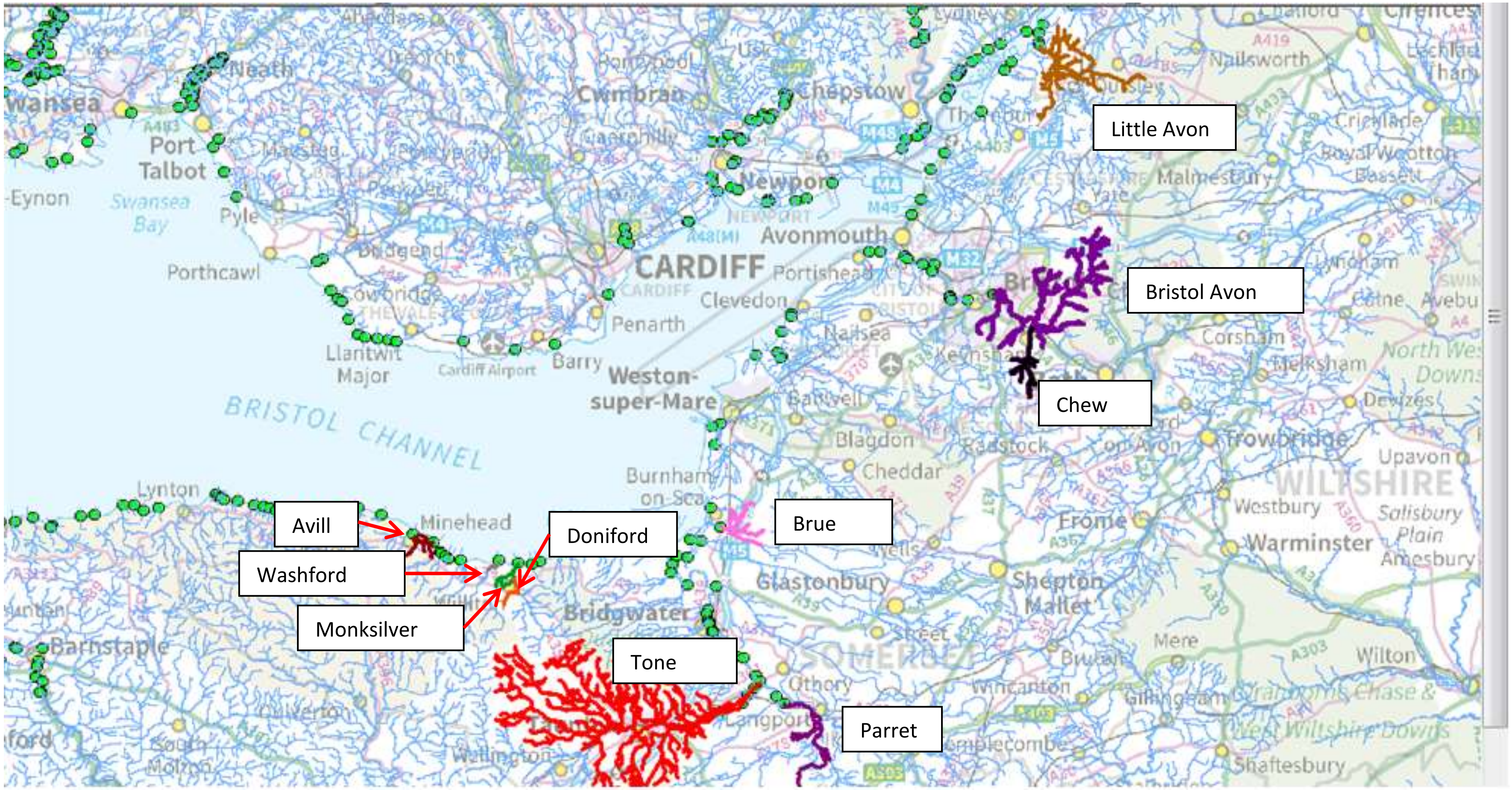


Figure 1 Map showing location of the English NEW rivers within the Environment Agency's South West Region .

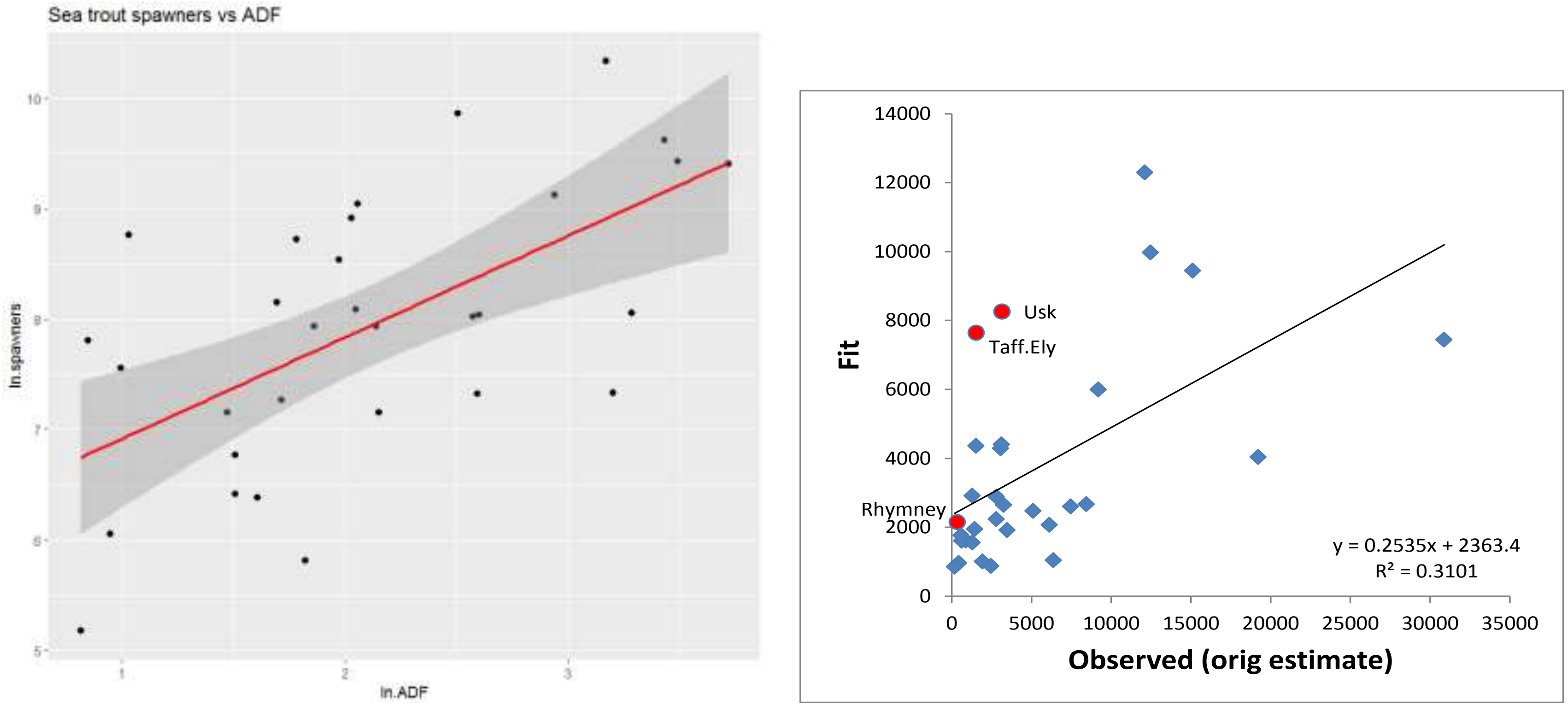


Fig 2A (left) Relationship between log spawners and log ADF for 31 Welsh rivers (parameters in Appendix II). Fig 2B (right). Model performance comparing fitted values against observed. Red circles show calibration rivers in this Hinkley Point assessment.

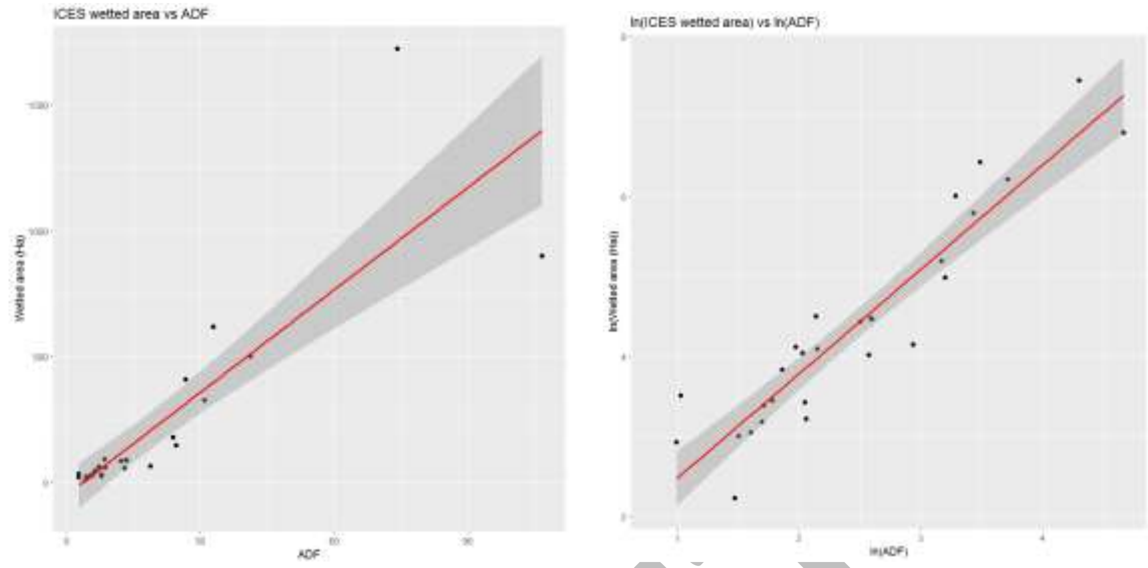
APPENDIX I.1 Model results, flow (ADF) *vs* accessible wetted area for Welsh rivers (including Severn and Wye)

Model with arithmetic data

```
wet area vs ADF (Wye and Severn included)
Arithmetic

Call:
lm(formula = wet.area.ices ~ adf.act, data = data)

Residuals:
    Min      1Q  Median      3Q     Max 
-500.77  -45.03   -1.22    8.84  762.59 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  -48.762     46.970  -1.038    0.309    
adf.act       13.567      1.599   8.487 5.74e-09 ***
---
Signif. codes:  
0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 191.9 on 26 degrees of freedom
  (5 observations deleted due to missingness)
Multiple R-squared:  0.7348,	Adjusted R-squared:  0.7245 
F-statistic: 72.02 on 1 and 26 DF,  p-value: 5.745e-09

> anova(mod.adf)
Analysis of Variance Table

Response: wet.area.ices
          Df  Sum Sq Mean Sq F value    Pr(>F)    
adf.act    1 2651958 2651958  72.021 5.745e-09 ***
Residuals 26  957375   36822                      
---
Signif. codes:  
0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
>
```

Model with logged data

```
Call:
lm(formula = ln.wta.ices ~ ln.adf, data = data)

Residuals:
    Min      1Q  Median      3Q     Max 
-0.8696 -0.2595 -0.0349  0.2611  0.9866 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  1.17209    0.25491   4.598 9.71e-05 ***
ln.adf       1.30492    0.09744  13.392 3.55e-13 ***
---
Signif. codes:  
0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.4736 on 26 degrees of freedom
  (5 observations deleted due to missingness)
Multiple R-squared:  0.8734,	Adjusted R-squared:  0.8685 
F-statistic: 179.3 on 1 and 26 DF,  p-value: 3.549e-13

> anova(mod.ln.adf)
Analysis of Variance Table

Response: ln.wta.ices
          Df Sum Sq Mean Sq F value    Pr(>F)    
ln.adf     1 40.222  40.222  179.33 3.549e-13 ***
Residuals 26  5.831   0.224                      
---
Signif. codes:  
0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```



Appendix Fig I.1 Comparison of arithmetic (left) and log-transformed (right) plots of ADF against accessible wetted area.

APPENDIX II Model parameters, anova, and plot(mean annual spawners vs ADF) in 31 Welsh rivers

```
SPAWNERS VS ADF MODEL FOR 2006-2016, EXC SEVERN AND WYE)

> ### MODEL
> mod.sp1 <-lm(data = data.spawn, ln.sp.0616 ~ ln.adf)
> par(mfrow = c(2,2))
> plot(mod.sp1)
> summary(mod.sp1)

Call:
lm(formula = ln.sp.0616 ~ ln.adf, data = data.spawn)

Residuals:
     Min       1Q   Median       3Q      Max
-1.85826 -0.81514 -0.01559  0.68611  1.81139

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   6.0000     0.5001  11.998  9.1e-13 ***
ln.adf        0.9184     0.2207   4.161 0.000258 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1 on 29 degrees of freedom
Multiple R-squared:  0.3738,    Adjusted R-squared:  0.3522
F-statistic: 17.31 on 1 and 29 DF,  p-value: 0.0002582

> anova(mod.sp1)
Analysis of Variance Table

Response: ln.sp.0616
          Df Sum Sq Mean Sq F value    Pr(>F)
ln.adf     1 17.322 17.3224  17.312 0.0002582 ***
Residuals 29 29.018  1.0006
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
>
>
```

APPENDIX III   Model outputs for calibration rivers, Wye and Severn

River	ref	Wetted accessible area ICES (Ha)	ADF, actual (m3s-1)	bfi	Observed spawners (2006-2016)	model fit	lwr 95% prediction CL	upr 95% prediction CL
Severn	*1*	*898.1*	*106.70*	0.51	*NA*	*29,409*	*2,729*	*316,920*
Wye	*2*	*1721.0*	*74.24*	0.55	*1,455*	*21,077*	*2,108*	*210,715*
Usk	3	407.1	26.77	0.60	3,148	8,260	4,336	15,735
Rhymney	4	NA	6.20	0.53	336	2,154	1,459	3,182
Taff.Ely	5	145.7	24.61	0.52	1,527	7,644	4,138	14,119
Ogmore	6	61.2	7.21	0.49	5,105	2,476	1,705	3,594
Afan	7	29.6	5.55	0.46	1,429	1,948	1,294	2,934
Neath	8	55.6	13.12	0.36	3,059	4,291	2,813	6,543
Tawe	9	87.8	13.37	0.41	1,521	4,366	2,850	6,686
Loughor	10	59.8	8.61	0.45	1,285	2,915	2,018	4,212
Gwendraeth	11	NA	4.52	0.46	872	1,612	1,020	2,549
Tywi	12	500.1	41.28	0.48	12,104	12,294	5,454	27,715
Taf	13	90.1	8.52	0.55	2,784	2,886	1,998	4,169
E.Wcleddau	14	86.6	13.49	0.55	3,105	4,403	2,869	6,757
Nevern	15	18.6	2.70	0.52	1,922	1,005	538	1,878
Teifi	16	325.9	30.99	0.51	15,108	9,448	4,693	19,023
Aeron	17	20.2	4.51	0.50	611	1,609	1,017	2,546
Ystwyth	18	46.1	6.45	0.50	2,790	2,235	1,522	3,283
Rheidol	19	30.6	7.77	0.44	3,248	2,652	1,834	3,833
Dyfi	20	179.1	23.89	0.48	30,877	7,440	4,071	13,597
Dysinni	21	31.5	5.94	0.48	6,122	2,074	1,394	3,084
Mawddach	22	56.7	7.61	0.34	7,453	2,602	1,799	3,765
Artro	23	NA	2.58	0.41	428	962	506	1,829
Dwyryd	24	9.2	4.36	0.39	1,281	1,559	977	2,490
Glaslyn	25	25.0	7.84	0.46	8,437	2,673	1,850	3,864
Dwyfawr	26	33.3	2.81	0.42	6,372	1,041	565	1,919
Llyfni	27	NA	2.33	0.47	2,456	877	444	1,732
Gwyrfai	28	NA	2.26	0.44	177	853	427	1,704
Seiont	29	21.1	4.99	0.51	591	1,766	1,145	2,722
Ogwen	30	23.9	5.45	0.43	3,460	1,916	1,267	2,895
Conwy	31	63.0	18.90	0.38	9,192	5,999	3,556	10,123
Clwyd	32	83.9	12.27	0.54	19,207	4,034	2,683	6,066
Dee	33	617.0	32.87	0.48	12,462	9,974	4,842	20,545